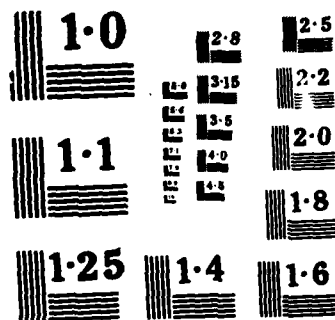END

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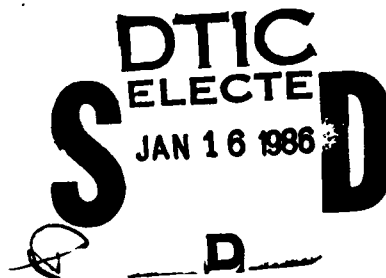
BASED ON COHERENT MODULATION

Final Report

Part I

G. Jacobsen

October 1985

United States Army

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Coherent optical communication systems have potential application possibilities which make them a very interesting research area. Compared to present optical communication systems operating at 1.3 μm or 1.55 μm they can operate with 20 dB's increase in receiver sensitivity which allows around 100 km increase in repeater separation for point to point transmission systems. In addition fully developed coherent systems will allow multiplexing and demultiplexing of several hundreds of information channels all transmitted via just one single mode fiber

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This could serve as the basis of a coherent local area wideband network.

In the present project at the Electromagnetics Institute, Technical University of Denmark a number of different coherent system components has been tested. Our main work has included results concerning

* generation of optical frequency modulation

* frequency stabilisation

* the transmission fiber

* injection locking of semiconductor lasers

* the coherent receiver

Our next target is complete design and test of a heterodyne system with independent transmitter and local oscillator laser.

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FOR PART I

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INTRODUCTION

Laser communications systems, as conceived in the mid 1960's were expected to use coherent detection to exploit the enourmous bandwidth potential of singlemode signals at optical frequencies.

However, the advent of semiconductor lasers with low coherence, and graded index fibers, moved the emphasis towards incoherent, multimode systems with direct detection for communication purposes, and until recently, coherent optical modulation and detection had been used only for certain sensor applications.

During the last few years the technology for making cabling and jointing singlemode fibers, and for launching light into them has advanced to the point of commercial realisability. In addition, various methods have been used successfully to increase the coherence of semiconductor lasers by reducing the linewidth first to a single longitudinal mode of the chip cavity with a linewidth of typically tens of megahertz and later by various external cavity configurations to a linewidth down to tens of kilohertz. Using these high coherence sources it is now possible to modulate the amplitude, frequency or phase of the emitted light and to perform heterodyne or homodyne detection using a laser diode as local oscillator.

Pumping with the local oscillator power a detection gain (compared to direct detection schemes) op up to around 20 dB is obtained. In effect the thermal noise influence on the reception is eliminated acheiving the quantum noise limited detection. The increased system sensitivity can be used to enhance the repeater spacing in the trunk network (the fiber attenuation at 1.55 m is app. 0.2 dB/km) or to increase the number of distribution points for future local area network wideband services.

A unique feature for coherent system technology is the possibility for transmitting thousands of frequency multiplexed channels over a signle fiber and to demultiplex effectively in the receiver. The Frequency Division Multiplexing (FDM) technique is possible because an effective channel separation in the

receiver is obtained using <u>electronic</u> filtering. This is a considerably more bandwidth efficient method than the use of <u>optical</u> filter in <u>W</u>avelength <u>D</u>ivision <u>M</u>ultiplexing (WDM) systems.

Fig. 1 shows in simple schematic form a classical optical communication system and a coherent system. The classical system uses a laser diode where the modulation is placed directly on the injection current to give in digital form an On-Off Keying modulation. The modulated signal is transmitted over an optical fiber which may be multimode or singlemode. For short distance applications the spectral properties of the signal is unimportant since the photo diode response is very broadband. Long distance applications may imply the use of single mode fibers and laser diodes of relative narrow spectral width. At the photo diode the optical signal variation is transformed into variations of the photo current and this is used in the receiver to recover the modulated signal.

In the coherent sustem two laser diodes with very pure spectra and emitting at close frequencies are used. One acts as a transmitter and the other as a local oscillator. The digital modulation is placed on the optical carrier wave (for instance using an external modulator as shown here) using Amplitude, Frequency or Phase Shift Keying. In this case a single mode optical fiber is applied to transmit the signal, because the demodulation process requires polarisation matching between the received signal and the local oscillator signal. In the receiver the two signals are recombined optically using a single mode fiber coupler or a beam splitter, and the photo diode acts as nonlinear element in the heterodyne detection to give a photo current output at the beat frequency between transmitter and local oscillator. Again the photo current output is used in the receiver to recover the modulation.

The work at the Electromagnetics Institute, Technocal University of Denmark in the area of coherent optical communications systems was initiated in spring 1981 and was partly funded by the U.S. Army Research Office from July 1982. The following sections of the report give our main results. During the course of work a number of very detailed publications habe been written, se the reference list 1 - 14. These references, together with a list of pertinent references from the literature are collected in a separate volume II of the final report. Readers are referred to reference 1 - 14 for technical details which are not found in the present text which will emphasize our results seen in the general connection with design of practical future coherent systems.
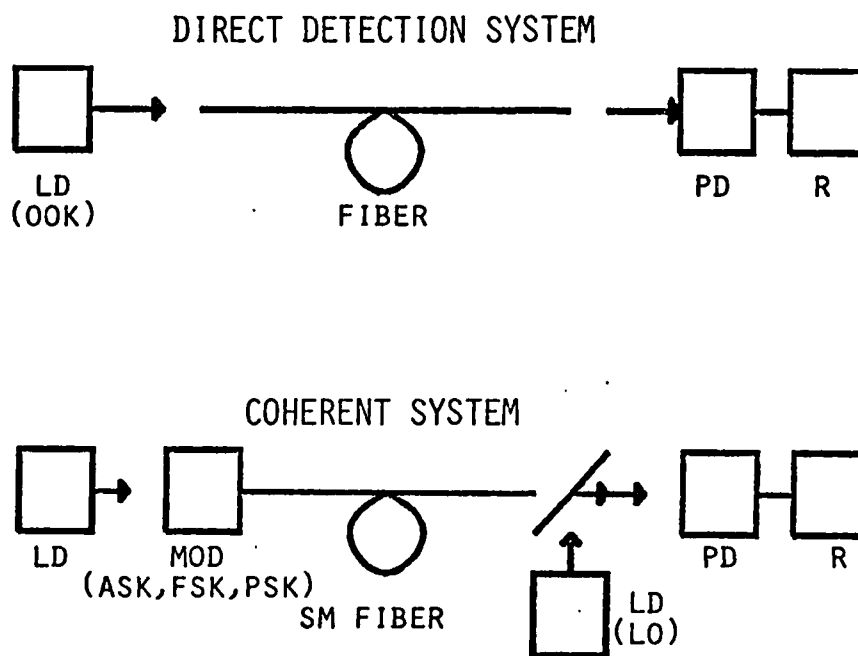
Fig. 1 Optical communications systems. LD - laser diode,
PD - photo diode, R - receiver, Mod - modulator,
A/F/PSK - Amplitude/Frequency/Phase Shift Keying,
SM - single mode, OOK - on off keying, LO - local
oscillator.

1. GENERATION OF OPTICAL FREQUENCY MODULATION

One way of generating optical FM is by modulating directly the injection current for a single mode semiconductor laser. Results were reported in refs. 1 - 4, The results are summarised below:

A detailed theoretical and experimental investigation of the spectral behaviour of a current modulated injection laser, was performed.

In the theoretical analysis a general formulation was presented for the laser field obtained from a combined intensity and frequency modulation (IM + FM). The theory is based on the knowledge of the current-to-frequency modulation transfer function (CF + MTF) for the laser. The general formulas for the resulting power spectrum show that it is obtained from a translation of the spectrum for the modulation function to the center frequency of the laser followed by a convolution with the spectral line shape of the unmodulated laser.

Numerical examples have been presented dealing with sinusoidal, sawtooth, and square wave (FSK) modulation. From the results it is obvious that the pure FM spectral shape is strongly influenced by the IM index and the phase delay between the IM and the FM part of the modulating signal. In the case of zero phase delay the spectrum becomes more and more asymmetric (skew) for increasing IM index with a relative increase of the lower sidebands. For a phase delay between 0 and $- \pi/2$ a similar conclusion is drawn although the skewness tendency is less pronounced for decreasing phase delay values. For a phase delay of $- \pi/2$ the spectrum remains symmetrical for increasing IM index, whereas the relative sideband magnitude changes significantly from the pure FM case. When the phase delay lies between $- \pi/2$ and $- \pi$ we obtain a reverse situation to the one for a delay between 0 and $- \pi/2$, resulting in a relative increase of higher sidebands.

Measurements of the power spectrum for a temperature stabilized CSP injection laser were taken using a Fabry-Perot interferometer (FPI). In such measurements a detailed understanding of the characteristics of the FPI and the detection system is essential in order to interpret the results correctly. A

thorough consideration of this problem has been given and is outlined. Taking the characteristics into account the measurements have confirmed qualitatively our calculation results, where we have considered broad-band and narrow-band FM cases for sinusoidal modulation as well as broad-band cases for sawtooth and square wave modulation. The results are in agreement with an earlier measurement of modulus and phase of the CF-MTF for this type of injection laser.

For application in practical digital Frequency Shift Keying (FSK) systems equalisation can be performed effectively using two terminal laser diodes instead of simple diodes (see [14]).

2. FREQUENCY STABILISATION

We have used a simple current based AFC-loop to stabilize the mean frequency
of singlemode lasers [6, 9] at 830 nm and 1.3 μm. The servo-loop consisted
of a FP cavity as frequency discriminator, a differential amplifier and an
integrator.

Convincing mean frequency stabilization was obtained with less than 1.3 kHz_{pp}
frequency variation over 30 min for the 830 nm laser and less than 66.3 kHz_{pp}
variation for the 1.3 μm laser. It was found that the 1.3 μm laser was con-
siderably less sensitive to optical reflections than the 830 nm laser giving
confidence to the development of coherent communication systems at 1.3 μm.
For the 1.3 μm laser it was possible to modulate the laser injection current
with frequencies larger than the active frequency range of the FP passband
and to lock to the carrier or one of the sidebands of the resulting IM-FM
spectrum. This technique in combination with locking to frequency standards
could possibly be used for simultaneous generalation of several local oscilla-
tor signals in future coherent frequency multiplexing communications systems.

Converting the relative frequency stabilities obtained here to absolute sta-
bilities in the kHz range could allow design of heterodyne systems without
direct stabilization of the IF. In homodyme systems such absolute stabilities
might allow the use of phase locked loops with small pull-in bandwidths for the
carrier regeneration circuit.

Future efforts could be devoted to the design of servoloops (electronically/
optically), that provide a simultaneous good mean frequency stability as well
as a reduced linewidth. Work at longer wavelengths (1.3 μm or 1.55 μm) could
be of special interest.

The work concerning mean frequency stabilisation and simultaneous linewidth
narrowing [9] is continued using a laser diode with an antirefelction coated
mirror against the cavity. Using also dispersive feedback in the cavity from
a grating a practical design of a frequency stable, line narrowed, optical
oscillator is now being tested.

3. THE TRANSMISSION FIBER

In a series of measurements at 1.3 μm wavelength it has been found that for
a linear polarised input signal to a conventional single mode fibre the out-
put polarisation drift is slow and can be compensated using a slow electronic
automatic polarisation control loop. Initial measurements used 10 km of
single mode fibre. The results were extended using 40 km of fiber. The re-
sults obtained are in agreement with results from British Telecom Laborato-
ries. From these results we conclude that conventional single-mode fibers
can be applied in future coherent communications systems provided a single
automatic polarisation control loop is developed. This gives an opportunity
for upgrading existing single mode fiber systems without changing the fibers.

4. INJECTION LOCKING OF SEMICONDUCTOR LASERS

Using injection locking of semiconductor lasers it is possible to generate optical Phase Modulation (PM) [5].

Our work with injection locking of semiconductor lasers have been summarised in refs. 7, 8, 10. In the references we present a general theoretical and experimental investigation og injection locking of semiconductor lasers. The theoretical model takes into account the dependence on the carrier density expressed by the linewidth enhancement factor α. Also included is the damping effect of spontaneous emission and - for a BH structure - lateral carrier diffusion. Locking conditions and dynamic stability is analysed. The non-zero value of α results in an increased locking bandwidth, where only part of the range corresponds to a dynamically stable state. Asymmetric characteristics are obtained for the locked power and phase as a function of frequency detuning between the master and slave laser. Outside the stable range light injection gives rise to beat phenomena and intensity pulsations. The theoretical results were confirmed by experiments on 830 nm CSP lasers and 1.3 µm BH lasers. The experiments include the first measurements of locking width characteristics reported for 1.3 µm lasers. Power spectra were recorded under locked and near locked conditions and compared with theory. The 1.3 µm lasers were found to have a better dynamic stability than 830 nm lasers. Even so, the stability problems may exclude the particular application of injection locking where phase modulation is generated for coherent transmission.

5. THE COHERENT RECEIVER

Using laser diode transmitters and local oscillators of zero linewidth it is possible to obtain a system sensitivity improvement up to around 20 dB as shown in Fig. 2. Design of practical systems may imply the use of non-ideal laser diodes. In a cooperation with British Telecom Research Laboratories we have derived a general theoretical model of receivers for coherent optical communication systems where transmitters and local oscillators having non-zero linewidth are used. Key issues in the model are the concept of single realisation measurements of a stochastic intermediate frequency, and development of the probability density function for this stochastic process. Analytical results are derived for heterodyne ASK and dual filter FSK receivers and include the shot noise limit, the asymptotic error probability limits in ASK and FSK receivers, the influence of the IF on receiver noise, and the effective local oscillator strengths. Detailed numerical results for typical pin-FET wideband receivers illustrate the influence on receiver sensitivity of IF filter bandwidth and relative threshold setting in ASK systems and of modulation index and IF filter bandwidth in FSK systems. A receiver sensitivity penalty for non-zero linewidth is found to be, for IF linewidths of 0.1 to 0.3 of the bit rate, 3 to 9 dB in optimum ASK receivers and 1 to 8 dB in optimum FSK receivers.

Thus DFB lasers of linewidth 5 to 20 MHz could be used without external cavities in simple systems with near ideal performance, which could find application wherever the great multiplexing capability of coherent systems is a prime advantage. We have derived guidelines for system design based on the results of this work. Our results are summarised in refs. 11 - 13.

Future work will consider receivers for DPSK systems and ASK/FSK systems including the influence of post detection filtering.

SYSTEM SENSITIVITY (LINEWIDTH ZERO, PEAK POWER BASIS)

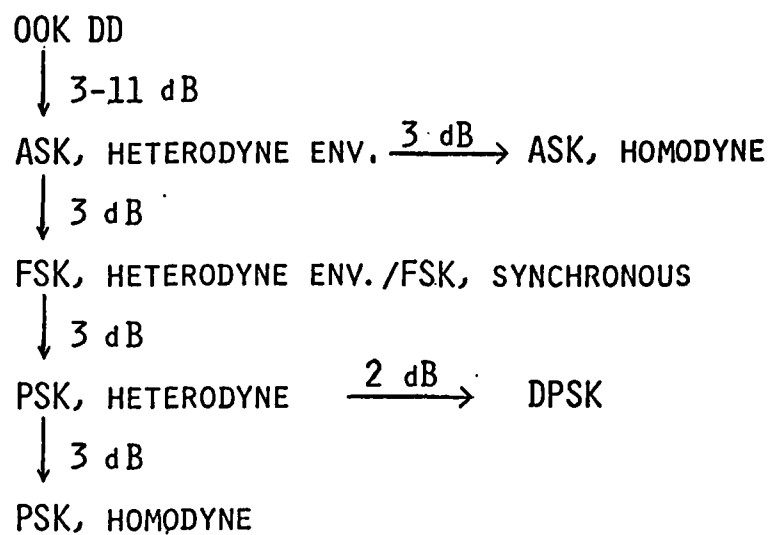OOK DD

$\downarrow$ 3-11 dB

ASK, HETERODYNE ENV. $\xrightarrow{3\ dB}$ ASK, HOMODYNE

$\downarrow$ 3 dB

FSK, HETERODYNE ENV./FSK, SYNCHRONOUS

$\downarrow$ 3 dB

PSK, HETERODYNE $\xrightarrow{2\ dB}$ DPSK

$\downarrow$ 3 dB

PSK, HOMODYNE

Fig. 2.

SUMMARY

During the last three years a number of different coherent systems components has been tested at the Electromagnetics Institute. Our main work has included results concerning

* generation of optical frequency modulation
* frequency stabilisation
* the transmission fiber
* injection locking of semiconductor lasers
* the coherent receiver

Our next target is complete design and test of a heterodyne system with independent transmitter and local oscillator laser.

The potential application for the coherent technology is seen as the tool for multiplexing and demultiplexing several hundred information channels as the basis for a coherent local wideband network.

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